

THOR4Ice: THickness from Offbeam Returns from Ice

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ABSTRACT

We propose to build a new airborne lidar system to measure sea ice thickness, snow thickness, and the topography of the Earth's cryosphere. In addition to its high range-resolution, the instrument's most distinguishing feature will be its multiple field-of-views for measuring the diffuse halo that forms in the ice around a laser beam's entry point. Snow and sea ice thickness is then retrieved based on the fact that thickness strongly influences the size and temporal evolution of the observed halo. Theoretical experiments and ground-based measurements have already confirmed the validity of this approach for sea ice, and a recent validation campaign demonstrated our ability to measure the thickness of clouds using airborne halo observations. Because our current instrument is optimized for cloud thickness measurements, we propose to build a new system that will have a much higher spatial and range resolution in order to resolve the topographical changes and diffuse halos that are much smaller in ice than in clouds. The proposed project will also include field demonstrations and a detailed analysis of requirements for space-based systems.

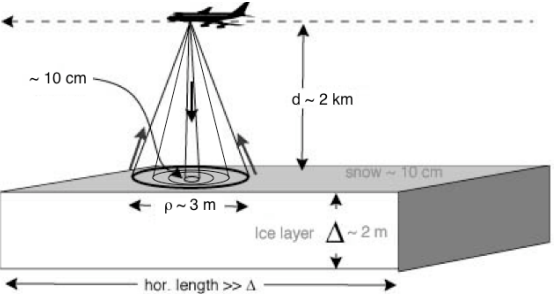
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I. OBJECTIVES AND SCIENTIFIC SIGNIFICANCE

This proposal seeks to build and test a new airborne lidar system that will measure sea ice thickness, snow thickness, and the surface and internal topography of ice sheets and glaciers. An overview of the proposed project is shown in Figure 1.

Figure 1: Overview of proposed project.

<p>Typical configuration of THOR4Ice observations P.I.: Robert F. Cahalan</p> 	<p>Description:</p> <ul style="list-style-type: none"> • Multiple field-of-view lidar (up to 5 mrad) • 15 cm range-resolution for 8 field-of-views • Optical fiber bundle to guide photons to detectors • Highly sensitive photon counting photo-multiplier tube (PMT) detectors <p>Objectives:</p> <ul style="list-style-type: none"> • Snow and sea ice thickness and internal properties from multi-view observations • Improved freeboard sea ice thickness using multi-view snow information • Topography of ice sheets
<p>Approach and Co-I's/Partners:</p> <p>NASA/GSFC provides leadership and optical engineering work. UMBC provides data analysis. Sigma Space Corp. does bulk of engineering work</p> <ul style="list-style-type: none"> ✓ R. Cahalan: project leadership ✓ M. McGill: oversight of engineering ✓ M. Sirota: project leader at Sigma ✓ T. Várnai: data processing & analysis ✓ J. Comiso: polar science <p>J. Kolasinski: optical subsystem</p>	<p>Schedule and deliverables:</p> <p>Year 1: Optical and detection subsystems construction, critical design review of system</p> <p>Year 2: Complete system integration, testing, and ground validation</p> <p>Year 3: •Test flights in polar environment, analysis of retrieval capabilities •Requirements and design concepts for space-based system</p>

Observing the topography of glaciers and ice sheets is essential for understanding the development of these ice masses and of their interactions with other components of the climate system. Among of the least known parameters associated with the sea ice cover are snow and ice thicknesses. Both parameters are crucial in the calculation of heat and salinity fluxes between the ocean and the atmosphere over ice covered areas. Snow and ice are good thermal conductors and have relatively high albedo, but their impact can vary considerably depending on thickness. Sensitivity studies using several global circulation models have also indicated that accurate values for the snow and ice thicknesses are required for consistent predictions.

Satellite techniques provide the only alternative for large scale spatial and temporal coverage that is required for global change studies. Results from studies using concurrent aircraft lidar and nuclear submarine sonar measurements have shown that the thickness distribution of sea ice as measured from a submarine can be reproduced using freeboard thickness distribution inferred from a ranging lidar (Comiso et al., 1991; Wadhams et al., 1991; Steffen and Heinrichs, 2001).

Satellite radar altimeter data have also been successfully used for similar studies (Laxon et al., 2003). A dedicated satellite mission, called CryoSat, is about to be launched because of the recognition of the importance of accurate measurements of the thickness of sea ice. A satellite lidar system, called IceSat, has also been around for 2 years (but not continuously because of a hardware problem) and the inferred freeboard data have been shown to provide useful thickness information. The CryoSat system is a delay-doppler radar altimeter system that measures the thickness of the ice freeboard but not of the snow cover. IceSat, on the other hand, measures the thickness of ice freeboard and snow cover combined. Accurate measurements of the actual ice thickness using either systems is possible only if the thickness of the snow cover is also known. The THOR4Ice system proposed here has the potential of measuring both thicknesses individually.

The proposed instrument's most distinguishing feature will be its multiple views for measuring the diffuse halo that forms in the ice or snow around the spot illuminated by the laser (see top left panel in Figure 1). The multiple field-of-view capability will be achieved by using a custom-made optical fiber bundle to channel photons from concentric circles at the telescope focal plane to a linear array of single photon counting detectors. While the actual viewed area will depend on aircraft altitude, a maximum viewing angle of 5 mrad will be suitable to observe from 2 km altitude the halos that extend to less than 10 m in sea ice.

The main benefits of multi-view halo observations will be to allow:

- Snow thickness retrievals that can help in the interpretation of altimetry data, and improve the accuracy of freeboard estimates of sea ice thickness
- Direct sea ice thickness retrievals not affected by uncertainties of freeboard methods
- Estimations of internal snow and ice properties

Because wider field-of-views imply stronger background signals that cause larger observational noise, the engineering model developed in the IIP timeframe will use the outermost field-of-views at night only. Still, the instrument will be operated during daytime as well, with the inner 4-5 field-of-views providing data for topographical and snow thickness measurements. We will switch to full day-and-night operations as soon as we can replace the initial spectral filters with angle-insensitive very narrow bandpass atomic line filters that are currently under development at the Los Alamos National Laboratory. Since bandwidths as narrow as 0.005 nm have already been demonstrated, we expect full day-and-night capabilities both for the airborne instrument proposed here and for the space-based instrument we hope to propose for an ESSP-type mission—although this may be achieved only past the IIP timeframe.

I.1 Principles of THOR4Ice retrievals

Topographical information will be extracted from central field-of-view data using existing methods (e.g., Krabill et al. 2002). The interpretation of structural and topographic signals from the outer halo field-of-views will use a new concept that has already proven successful for retrieving sea ice thickness from optical measurements at the top of the ice, as shown in Figure 2 (Haines et al. 1997, Trodahl et al. 1987, Buckley and Trodahl 1987). We used this concept to measure cloud thickness using airborne observations by the cloud-observing THOR (THickness from Offbeam Returns) instrument. Comparisons with ground-based data showed a retrieval accuracy of 5% or better for the observed clouds, whose thicknesses ranged from 500 m to 1 km (Cahalan et al. 2004a).

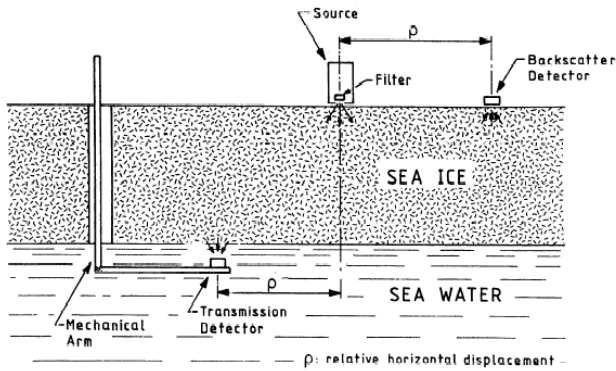


Figure 2: Schematic graph from Haines et al. (1997), showing the experimental setup of in-situ ice thickness measurements. We note that the ice thickness and scattering coefficient values are retrieved using only the reflectance measurements—the transmission measurements are used only for estimating the anisotropy of brine pockets and the absorption by algae.

The basic idea is to illuminate the ice with a laser beam at a point (x_0, y_0) , and to measure the off-beam reflectance that emerges from the ice at various

distances from this point. The geometrical thickness is then retrieved from the way reflectance decreases with the distance from (x_0, y_0) and from the observed time-dependence of wide-angle signals: Extensive theoretical studies showed that diffusion makes light to spread farther and spend more time in thicker media (e.g., Kornreich and Ganapol 1997, Davis and Marshak 2002).

Naturally, the spread of light depends not only on the geometrical thickness, but also on the absorption and scattering properties of ice. Absorption of visible light is caused primarily by the ice crystals themselves (except for a thin layer of algae at the bottom of the ice (e.g., Mobley et al. 1998)), and so the volume absorption coefficient of sea ice remains close to the laboratory measurements of Grenfell and Perovich (1981). In contrast, scattering is caused by small impurities in the ice—air bubbles, brine (small pockets of melted water), and small ice crystals (that form if the ice temperature dips below the eutectic point around -21°C)—whose concentrations can vary in a wide range. Because brine channels are often elongated in vertical direction, the scattering coefficient of sea ice is often anisotropic, with stronger scattering of horizontal than vertical light. Also, the calculations need to consider at least two ice layers: the relatively transparent bulk ice and a thin turbid layer at the top, which is much more opaque due to the higher concentration of scatterers such as air bubbles (e.g., Haines et al. 1997, Mobley et al. 1998). Of course, any snow on top adds an additional layer or layers with intense scattering.

Though our ice/snow simulations assume simplified ice/snow layer structures, we will make these as realistic as the data allows, including multiple sub-layers with variations in snow grain size, density, and opacity, appropriate for the wide range of ice types observed (Allison and Brandt 1993; Warren et al. 1997, 1999; Massom et al. 2001). The outer channels of THOR4Ice are insensitive to details of scattering phase functions because they are in the diffusion domain, but the innermost channels may give information on grain size and variations in sub-layers.

Similarly to the work of Haines et al. (1997), the proposed system will simultaneously retrieve the scattering coefficient and geometrical thickness of all distinct layers. Multi-layer retrievals are possible because the innermost measurements are dominated by scattering in the near-surface layers, whereas the measurements farther from the illuminated point tell about the properties of the entire ice sheet.

Figure 3 shows a simulated return signal for a hypothetical system that—for better visual clarity—has a very short pulse duration. The figure shows that the central channel observes intense direct backscatter from near the ice surface, while the outer channels observe a fainter halo formed by multiple scattering deep inside the ice. The signal of outer channels is delayed because photons need time to reach the halo’s outer portions, and it is stretched, because some photons meander more, while others follow more straight paths.

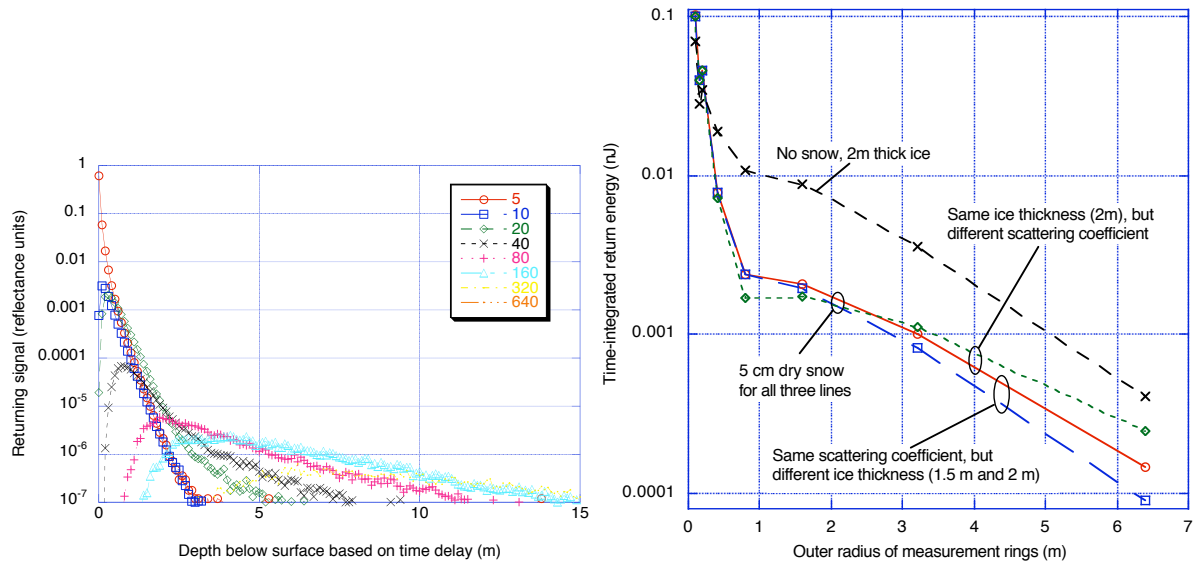


Figure 3: (Left) Simulated THOR4Ice data for 2 m thick ice covered by 15 cm snow. The legend indicates the outer radius of each field-of-view. (Right) Time-integrated return signals for various snow and ice conditions.

Direct snow and sea ice thickness retrievals will work by comparing the halo observations to pre-calculated look-up tables obtained from 3D Monte Carlo radiative transfer simulations. The retrieval methodology will be similar to the iterative one used for clouds (Cahalan et al. 2004a), although it will be optimized for ice retrievals.

Let us note that the retrievals will need to consider the contribution of atmospheric scattering to the spreading of light. Because cloud scattering will dominate over the signal from the ice, ice retrievals will require the absence of low clouds. We will detect clouds by monitoring the signal returned from altitudes higher than sea level.

I.2 Expected accuracy

The most important factors determining the accuracy of THOR4Ice altimetry measurements are the accuracy at which the GPS receiver can determine the instrument position and attitude, and the stability and of laser and instrument calibration (Krabill 2002). We expect that the accuracy of THOR4Ice altimetry measurements will match the (7-8 cm) accuracy of current state-of-the-art instruments such as the Airborne Topographic Mapper (ATM).

The accuracy of freeboard sea ice thickness measurements is determined by a combination of uncertainties in altimetry measurements, in sea level, and in snow thickness and density. THOR4Ice multi-view halo observations are expected to greatly reduce freeboard ice thickness uncertainties by providing independent information on snow thickness and density.

The uncertainty of halo-based snow and sea ice thickness retrievals were estimated through 3D radiative transfer simulations. For these simulations we used a Monte Carlo model that had been tested in the Intercomparison of 3D Radiative Codes (I3RC) (Cahalan et al. 2004b) and had been used successfully in THOR cloud thickness retrievals (Cahalan et al. 2004a). For ice simulations, the model was extended to include features specific to sea ice, such as refraction at ice boundaries and preferential vertical alignment of brine pockets. The uncertainty tests involved generating look-up tables for a wide range of ice parameters, simulating hypothetical

observations that were affected by various factors causing uncertainties, and finally, performing hypothetical retrievals. The sensitivity matrix in Table 1 lists the estimated uncertainties for 2 m thick sea ice covered by 15 cm dry, somewhat compacted snow. Although thick snow cover can reduce ice signal levels sufficiently to make halo-based ice retrievals impossible, the results in Table 1 indicate that halo-based ice thickness retrievals will work well (~10% uncertainty) over many polar areas. This is because snow tends to be fairly thin in some regions—for example Massom et al. (1998) estimated that only about 15% of East Antarctic sea ice is covered by snow thicker than 20 cm—and because thicker snow is often older, more compacted, and so not significantly more opaque than a thin layer of fresh snow. Whenever snow, ice, or background illumination conditions will prevent halo-based ice thickness retrievals, we will revert to freeboard sea ice thickness estimations aided by halo-based retrievals of snow thickness.

Signal levels from the much more intensely scattering snow will be much higher than from ice, and we expect reliable snow retrievals even when halo-based ice retrievals are not possible. (For example, observation noise causes only 1.3 cm uncertainty in retrievals of 40 cm thick dry, somewhat compacted snow at 1 m resolution even for 50° solar elevation.) The higher signal level and smaller halo size will allow snow retrievals at high spatial resolution (~1 m), which will greatly reduce the effects of horizontal variability in snow thickness in our retrievals. As a result, we expect snow retrieval accuracy to be around 5 cm.

Table 1: Sensitivity matrix for sea ice thickness retrievals. (Section III.1 discusses the signal and noise levels used.)

Cause of uncertainty	Assumed typical conditions	Retrieval uncertainty
Observational noise in nighttime measurements	Full moon at 20° elevation, results of 20 m resolution retrievals averaged over 200 m	12 cm
Errors in relative calibration	2% calibration accuracy	6 cm
Horizontal variability in ice thickness	0.5 m ice thickness difference between two halves of observed area	5 cm
Vertical variability	20% random variations for 10 cm thick ice sub-layers	15 cm
Algae at ice base	3 times more intense absorption in bottom 5% of ice	1 cm
Overall uncertainty	Errors caused by different sources are independent	20 cm

I.3 Comparison to other ice observations

While the proposed system certainly has important limitations—lack of cross-track imaging capability, inability to take ice measurements through clouds, somewhat limited daytime operations—it also has ample advantages:

- In contrast with other lidar and radar ranging instruments, THOR4Ice will provide information on the internal structure of the snow/ice cover. Most importantly, THOR4Ice will provide vertical profiles of the extinction coefficient, thus yielding information on snow thickness and opacity—as well as on the concentration of scatterers in sea ice. This can be of great value in and of itself, but it can also help in the interpretation of altimetry measurements. For example, snow information can greatly reduce the uncertainties in freeboard estimates of sea ice thickness. (Because a certain error in assumed snow thickness can cause several times larger errors in the retrieved sea ice thickness, the lack of snow information can cause uncertainties over a meter in freeboard estimates of sea ice thickness.) This is especially significant in polynyas and other areas of possible thin ice.
- Unless the snow cover is very thick, nighttime THOR4Ice halo observations will provide direct measurements of sea ice thickness, independently from freeboard. These estimates are most needed in areas without open water suitable for direct sea level observations, where the combined uncertainties in sea level and instrument position exceed 5 cm (Krabill et al. 2002), and can reach much higher values because of uncertainties in geoids or tides. Such uncertainties can be important because they result in 9 times larger uncertainties in freeboard sea ice estimates (90% of sea ice is below sea level).
- Unlike radar retrievals of sea ice thickness, THOR4Ice retrievals will not be significantly contaminated by sub-resolution leads and melt ponds. Even at the 1 km resolution of ESA's CryoSat satellite expected to launch in early 2005, about 20% of the sea ice cover will not be measured, missing the small floats and areas near leads (Wingham 1999, p. 37). In contrast, THOR4Ice will use a field of view of only a few meters, and so it can work even in broken ice sheets or small floats. The lidar pulses that reach deep water can be identified easily and excluded from the calculation of area-average sea ice thickness values.
- In contrast with coarse-resolution radar measurements, THOR4Ice's small footprint (< 15 m diameter) will allow it to yield information on surface roughness and detailed histograms of ice thickness distributions. Accurate histograms are very important (Wadhams 1995), for example because the ridges due to the compression of ice floes contain a large percentage of ice mass, control the momentum exchange with the atmosphere, and influence ice rheology (Grey and Morland 1994).

II. THOR CLOUD RESULTS

Offbeam lidar signals were first detected from clouds in 1997 by deflecting the beam of the upward-looking Goddard Lidar system detector several degrees (Davis et al, 1997). A wide-angle optical system was then designed and built, and the thickness retrieval method was verified for clouds by flying over the Oklahoma ARM site in March 2002. Figure 4 shows the THOR system mounted on the NASA P-3, and also, some typical data from 1 central and 7 offbeam channels. Comparisons of THOR retrievals with ground-based data showed a retrieval accuracy of better than 5% for 500 m to 1 km thick clouds (Cahalan et al. 2004a).

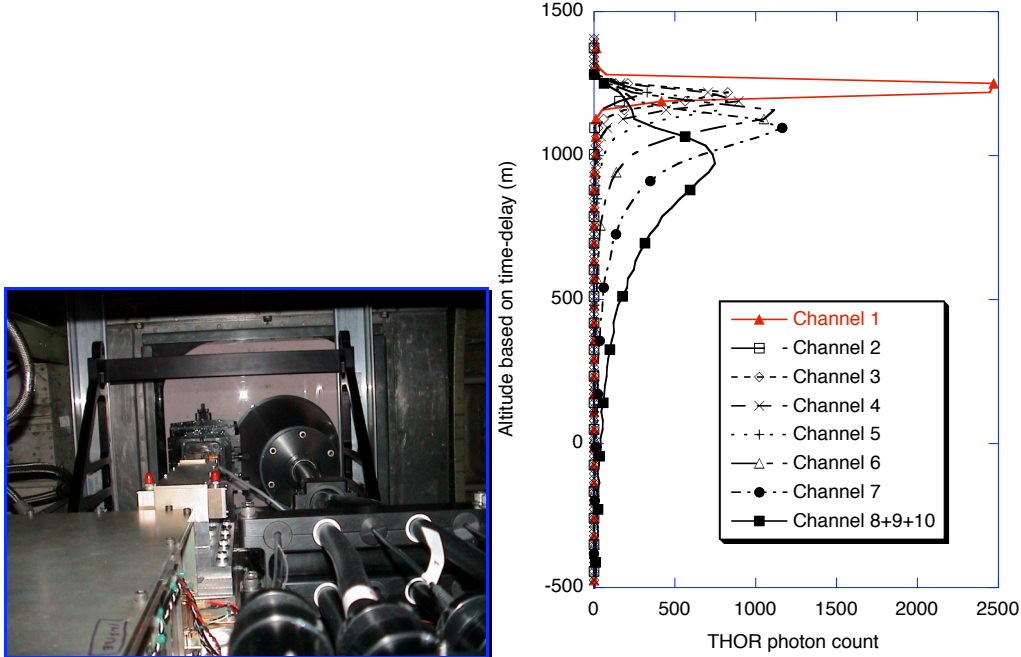


Figure 4: (Left) A down-looking photo of the THOR system mounted on the NASA P-3, during observations of cloud layers over the DoE ARM site in Oklahoma. 540 nm laser and beam expander are center left. Telescope is center right (in this case directed toward a nadir viewing port). Fiber bundle is lower right, connecting to detector array, also lower right, with data system on lower left. (Right) A sample of THOR cloud observations for a typical retrieval segment, collected during the 2002 THOR validation campaign.

III. PROPOSED WORK

III.1 System engineering

A novel THOR4Ice instrument will be designed, built, and tested, greatly leveraging on our experience with the cloud-observing THOR instrument. For example, the multiple field-of-views of THOR4Ice will be calibrated using the methods used for the cloud-observing THOR instrument (Cahalan et al. 2004a). The main differences from the cloud-observing THOR are as follows:

- tighter views (20X reduced)
- nanosecond timing (1000X reduced)
- uniaxial design
- smaller volume and weight (~4X)
- autonomous operation.

We will develop the THOR4Ice instrument to be compatible with one of the larger UAV aircraft, such as the Global Hawk. Our long-term objective is, in fact, to fly the new instrument on a UAV. The UAV platform is particularly attractive as it facilitates extended flight hours and mitigates personnel safety issues in flights over the Antarctic ice region. However, we will make certain the form factor also fits other aircraft, in particular the WB-57, to permit low-cost test flights. Our experience with other airborne lidar instruments, in particular with the Cloud Physics Lidar (CPL) (McGill et al., 2002), shows that well-designed instruments developed for the ER-2 or WB-57 can easily be adapted to the Global Hawk. All system design will be compatible with future design of a small, lightweight, compact spaceborne system. Nominal instrument parameters are shown in Table 2.

Because the 8 ns-long laser pulse stretches over 8 time bins, the reflection from a single altitude bin is distributed among 8 time bins. Therefore even short time-periods such as 0.1 s (which, considering typical flight speeds, corresponds to ~ 10 m spatial resolution) will have sufficiently fine dynamic resolution. (A square pulse shape would allow 800 levels, for realistic pulse shapes we expect 2-300 levels). The dynamic resolution is even better for the outer channels, whose return signal is more stretched in time (Figure 3).

The signal level of inner channels will be very high, requiring the use of neutral density filters. For thick snow, the low signal level of outer channels can become a major limiting factor of retrieval performance. Because multi-view halo retrievals combine data from various field-of-views and range bins, retrieval accuracy cannot be linked uniquely to the signal-to-noise ratio of any particular channel or range bin. Instead, we estimated signal-to-noise ratios for all channels and range bins using the equations in Cahalan et al. (2004a), and added random noise to simulated observations accordingly. Test retrievals using these noisy data and assuming the instrument parameters in Table 2 indicated the accuracy achievable listed in Table 1. The traceability matrix in Figure 3 shows photon counts for the situation in Table 1 in Section I.2.

Table 2: Nominal THOR4Ice parameters

Laser wavelength (nm)	539.8
Pulse repetition rate (Hz)	1000
Pulse energy (mJ)	0.225
Laser divergence (μ rad)	0.325
Telescope diameter (mm)	190.5
Telescope FOV range (mrad)	0-5.3
Number of detector channels	8
Spectral width of receiver (nm)	7
Range resolution (m)	0.15
Typical flight altitude (m)	2,000
Maximum flight duration (hours, WB-57)	6.5

Table 3: Traceability matrix for instrument parameters in Table 2 and ice conditions in Table 1. Losses in optical system are similar to those in cloud-observing THOR instrument.

# of photons emitted by laser	$1.2 \cdot 10^{17}$
# of photons captured by telescope for Channel 6, based on Monte Carlo tests	600
# of photons entering fibers (50% loss)	300
# of photons leaving back end of fiber bundle (4% loss)	288
# of photons passing through spectral filter (15% loss)	245
# of photons counted (10% efficiency)	~ 25
Signal-to-noise ratio for conditions in Table 1	~ 5
Retrieval accuracy after averaging over 200 m	$\sim 10\%$

III.1.1 Optical System Design

Laser. The laser required for this system will be a small, low power, commercially available model with a fairly high pulse rate (> 1 kHz) and short pulse duration (5-8 ns). The wavelength will be in the 530-550 nm range, where absorption by both ice and algae living in ice are small (Grenfell and Perovich 1981; Arrigo et al. 1991). *No laser development is required for this project, and obtaining a suitable laser does not carry any significant risk to the project.*

Telescope. During the instrument design phase, careful attention must be given to the wide field of view (~ 5 mrad full angle) telescope. In particular, the telescope must have a uniform response across all angles, and the aft optics must be telecentric to properly match the fiber bundle. To ensure that the telescope is properly designed, we intend to work with the optical designer who designed the telescope for the cloud-observing THOR instrument (Figure 5).

Signal Delivery. Another critical element of the optical system is the custom fiber bundle, which channels photons at the 8 fields of views to their respective detectors. To keep the signal level of outer field-of-views high, the radius of each FOV doubles relative to its inner neighbor. For 2 km flight altitude, the innermost channel covers an 8 cm diameter area, while the outermost channel reaches from 5 to 10 m diameter. Development of the fiber bundle is highly leveraged by previous work at GSFC. Thus, for purposes of this effort we consider the fiber bundle to be demonstrated and ready for use. The main difference from the bundle used in the cloud-observing THOR instrument is that, because the narrower field-of-view telescope will produce a smaller image at the focal plane, the new bundle will be about 5 times thinner.

III.1.2 Mechanical Design

The mechanical engineering effort for THOR4Ice will involve a novel design and packaging of the next generation, flight ready lidar instrument. THOR4Ice will be installed on the WB-57 aircraft, and interfaced accordingly, packaged in a pressure vessel. Sigma will leverage its experience in CPL instrument packaging for ER-2 and WB-57 aircraft towards THOR4Ice, thus minimizing risk on the mechanical design effort.

III.1.3 Electronics and Data System Design

The system will use commercially available fast (1 GHz) single photon counting photo-multiplier tubes (PMT's) for all field-of-views. The signal from all detectors will be combined by a custom data system that can process 1 GHz signals for up to 10 channels. The data system being proposed for THOR4Ice will be based on a system been developed under a Phase II SBIR, which is currently being tested for the Cloud Physics Lidar on the WB-57 platform. This effort will also be leveraged by adapting the data system for THOR4Ice.

III.2 Data processing

The proposed project will have a simulation and data processing component that will include:

- Developing a model to simulate THOR observations using realistic system characteristics and ice properties, to aid in system design and data processing. (Years 1-2.)
- Developing a prototype data processing software. (Years 2-3)
- Interpreting test measurements, performing error analysis. (Year 3)
- Developing system requirements for a future space-based instrument. (Year 3)

III.3 Ground Validation

A key milestone at the end of Year 2 will be ground validation. In situ snow and ice depth measurements, to a typical accuracy of 2 cm, will be compared to THOR4Ice retrievals on known targets, using established methods. Initial validation will be on site at Goddard, then over nearby snowfields over the relatively flat Delmarva Peninsula, near Wallops Flight Facility. This will facilitate later aircraft comparisons near Wallops, and also over western topography where snowfall is crucial to water supplies, and where comparisons can use the network of SNOTEL (SNOW TELemetry) stations of the USDA-NRCS National Water and Climate Center. (See <http://www.wcc.nrcs.usda.gov/snow>) These will be coordinated with related MODIS validation efforts, facilitated by the PI's participation on the MODIS Science Team, and by Col Comiso's expertise in snow/ice retrieval.

Comparison will be made to MODIS and AMSR-E validations of snow depth (e.g. <http://icerd.engr.ccny.cuny.edu/noaa/html/research/hydro/snowfall/satellite-index.html>) as well as ice thickness (e.g. <http://modis-snow-ice.gsfc.nasa.gov/lake.html>). Separation of snow and ice thicknesses will be tested for various MODIS and AMSR-E classifications of increasing complexity, as well as IceSat and Cryosat where available.

III.4 Field experiment

During the third year of the project we will perform a field experiment to test airborne instrument performance and to validate the snow and ice retrieval methodologies. The experiment will involve ground-based control measurements of ice and elevation, snow thickness, and, as much as possible, sea ice thickness. The exact timing and location of this field experiment are yet to be determined, but we expect an approximately two-week long campaign in North America in the winter of 2007-2008. As mentioned in Section III.1, we will use the NASA WB-57 aircraft.

IV. TECHNOLOGY READINESS LEVELS

While some components (such as lasers and detectors) will be commercially available models that are at TRL 5, other components are currently at TRL 3 or 4. This is particularly true for the custom fiber optic bundle, for the telescope, and for the high-speed data system. Upon completion of the proposed work, the TRL for the components and for the THOR system as a whole will be TRL 6, ready for application in future missions. **Operation of the THOR system on the NASA WB-57 will provide a demonstration at TRL 6.**

V. MANAGEMENT PLAN

Responsibility will reside at Goddard, with the PI directing telescope and fiber bundle design and integration with detection and data systems, ground and airborne observations, and reporting. Co-I McGill will oversee the instrument design and engineering work. Co-I Várnai will perform the data analysis tasks described in Section III.2. Co-I Comiso will advise in polar science issues and will help planning and performing the field experiment. John Kolasinski will work on the optical fiber bundle and on its front and rear interfaces to other components, and will

be responsible for the calibration of THOR4Ice channels. The telescope will be designed by Luis Ramos-Izquierdo, who designed the telescope of the cloud-observing THOR system. The new multi-channel data system will be built by ASRC Aerospace Corporation.

Our industrial partner, Sigma Space Corp. is the leading lidar instrument developer in the GSFC supplier community. Sigma is lead by Dr. Marcos Sirota, who has committed to THOR4Ice Incubator substantial Sigma resources, personnel continuity, and facilities. Sigma Space will design the system, integrate the components, and test the complete system under the direction of Co-I Marcos Sirota.

We will hold bi-weekly team meetings to discuss progress and issues from all groups. These meetings will be used to continually assess if each area is making satisfactory progress or there are any problems that need extra attention or require a change in approach. Any significant findings or change in direction will be reported to the IIP program manager. Our schedule plans for transitions in the phase of research and development at roughly year intervals from award. These transitions define our milestones listed in Section VI. Each milestone success criteria is the successful transition of that phase to the next related phase on the project schedule. If we are unable to transition into the next phase of development according to the schedule then we will assess rationale and develop recovery plans. At the end of the first year there will be critical design reviews on most activities. Interim reviews at about the 6 month point will be conducted to assess the research status and adjust the schedules if required.

VI. MILESTONES, TIMELINE, AND SUCCESS CRITERIA

Table 4 lists the milestones for each year and Table 5 shows the proposed timeline.

Table 4. Milestones (major milestones are bolded)

(FY1) laboratory observations, design work, and component construction:

- ✓ 1. design of optical and detection subsystems
- ✓ 2. mechanical design
- ✓ 3. acquisition and lab testing of components
- ✓ 4. construction and testing of optical and detection subsystems
- ✓ **5.** critical design review of first-year achievements

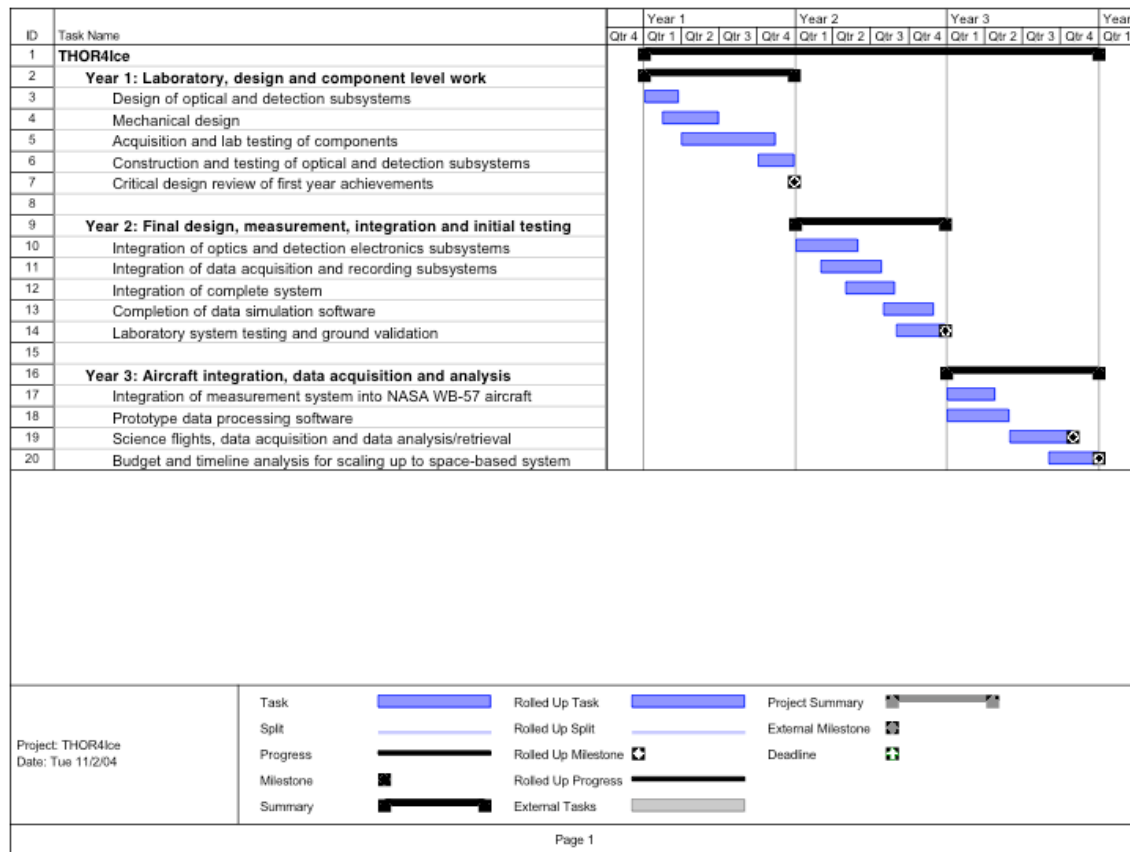
(FY2) final design, measurement system integration and ground-based testing:

- ✓ 6. integration of optics and detection electronics subsystems
- ✓ 7. integration of data acquisition and recording subsystems
- ✓ 8. integration of entire system
- ✓ 9. completion of data simulation software
- ✓ **10.** laboratory system testing and ground validation

(FY3) aircraft integration, data acquisition and analysis:

- ✓ 11. integration of measurement system into NASA WB-57 aircraft.
- ✓ 12. prototype data processing software
- ✓ **13.** science flights, data acquisition and data analysis/retrieval
- ✓ **14.** budget and timeline analysis for scaling up to space-based system.

Table 5: Timeline of proposed project.



Overall success criteria is simple: operation of the THOR system onboard the NASA WB-57, demonstration of halo-based snow and ice retrievals, and development of detailed concepts for a space-based system will constitute a successful project. We will evaluate the feasibility and cost of space-only issues that are no problem for aircraft, such as focusing the laser beam and measuring the close halo around the beam's entry point, required laser power, etc. Success in first year (milestone 5) will be completion of telescope, fiber bundle, and data subsystems and passing a critical design review. Success in Year 2 (milestone 10) will be ground operation and validation of integrated system, ready for test flights. Year 3 success is airborne science data acquisition (milestone 13), and report on space-based system (milestone 14).

VII. FACILITIES AND EQUIPMENT

Goddard provides excellent laboratory and computing facilities. Sigma Space Corporation provides its facilities dedicated to lidar system development. Sigma's facilities, located in Lanham, Maryland, consist of 16000 sq. ft. of office and laboratory space. Scientists and engineers are provided with state-of-the-art analysis software tools such as C++, Matlab, Mathcad, IDL, plus Pro-E and IDEAS for mechanical design, Zemax for optical design, and Orcad for electrical design. Facilities include an optical laboratory with several vibration isolated optical benches and a collimator for aligning sensitive optical instruments. Two Class 10,000 clean rooms equipped with advanced electronic instrumentation and assembly equipment are also available. Fabrication of mechanical parts is carried out in Sigma's machine shop that is equipped with a computer-controlled CNC machine, lathe, drill press and metrology equipment. A full suite of electronic testing equipment is available for electronics development, as well as workstations equipped with data acquisition hardware and software such as C/C++, Labview and Labwindows.

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Attachment A: Key Personnel

1 Robert F. Cahalan, Principal Investigator, Office: 301-614-5390; Cell:301-905-2611

Education: Ph. D., Physics, University of Illinois-Urbana, 1973

Present positions: 2003- Head, Climate and Radiation Branch/913, NASA/Goddard
2003- NASA Representative to U.S. Climate Change Science Program
2002- Visiting Senior Scientist, UMCP, ESSIC
1998- Adjunct Professor of Physics and JCET Fellow, UMBC

Research: climate modeling, remote sensing, empirical analysis methods, radiative transfer

Professional Society Memberships:

American Meteorological Society, American Physical Society, European Geophysical Union

Work Experience:

1978-1979 Senior Postdoctoral Fellow, National Center for Atmospheric Research
1977-1978 Visiting Assistant Professor, Department of Physics, U. of MO-St. Louis

Relevant Professional Activities:

NASA Project Scientist of EOS-SORCE Mission
International Radiation Commission, Member and Chair of 3D Working Group
NASA/DOE Project Scientist of Int'l Intercomparison of 3D Radiation Codes (I3RC)
NASA EOS-Landsat Science Team (1984-1988,1997-) & NASA-FIRE Team (1986-92)
DOE Unmanned Aerospace Vehicle Science Team (1995 -)
DOE Atmospheric Radiation Measurement (ARM) Science Team (1997 -)

Recent Relevant Publications:

Cahalan, M. McGill, J. Kolasinski, T. Varnai, and K. Yetzer, 2004: THOR – Cloud Thickness from Offbeam lidar Returns, *J. Atmos. Ocean. Tech.*, in press.
Cahalan, R. F., L. Oreopoulos, A. Marshak, K. F. Evans, A. Davis, R. Pincus, K. Yetzer, B. Mayer, R. Davies, and I3RC participants, 2004: The International Intercomparison of 3D Radiation Codes (I3RC): Bringing together the most advanced radiative transfer tools for cloudy atmospheres. *Bull. Amer. Meteor. Soc.*, in review.
Rozwadowska, A. and R. F. Cahalan, 2002: Plane-parallel biases computed from inhomogeneous clouds and sea ice, *J. Geophys. Res. – Atmospheres*, **107**, 4384-4401.
Davis, S. Love, R. F. Cahalan, and M. McGill, 2002: Off-beam lidar senses cloud thickness and density, *Laser Focus World*, **38**, 101-104
Cahalan, R. F., M. McGill, A. Davis, C. Ho, and S. Love, 1998: Physical and optical cloud thickness from off-beam lidar, *Laser Radar Tech. Conf. of the EU Symposium on Remote Sensing.*, Barcelona, Sept. 1998.
Cahalan, R. F. and L. S. Chiu, 1986: Large-Scale Short-Period Sea Ice-Atmosphere Interaction, *J. Geophys. Res.*, **91**, 10709-10717.

2 Matthew McGill, CoI, NASA/GSFC Code 912, Voice: 301-614-6281, Fax:301-286-1762

Education: Ph.D., Atmospheric Sciences, University of Michigan, 1996

Present position: 1997-present Phys. Sci., Lab. for Atmospheres, NASA/GSFC

Research: Lidar remote sensing, Doppler lidar, radiative transfer, atmospheric dynamics, interferometry.

Awards & experience: US Patent #6313908 for holographic circle-to-point converter; Project Scientist for CloudSat and PICASSO (radar and lidar in space) missions.

Cahalan, R.F., M.J. McGill, J. Kolasinski, T. Várnai, and K. Yetzer, "THOR – Thickness from Offbeam Returns lidar," *Journal of Atmospheric and Oceanic Technology* (2004, *in press*).

McGill, M.J., L. Li, W.D. Hart, G.M. Heymsfield, D.L. Hlavka, P.E. Racette, L. Tian, M.A. Vaughan, and D.M. Winker, 2004: "Combined lidar-radar remote sensing: initial results from CRYSTAL-FACE," *Journal of Geophysical Research*, **109**, doi: 10.1029/2003JD004030.

McGill, M.J., D.L. Hlavka, W.D. Hart, E.J. Welton, and J.R. Campbell, 2003: "Airborne lidar measurements of aerosol optical properties during SAFARI-2000," *Journal of Geophysical Research*, **108**, doi: 10.1029/2002JD002370.

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McGill, M.J., D.L. Hlavka, W.D. Hart, V.S. Scott, J.D. Spinhirne, and B. Schmid, 2002: "Cloud Physics Lidar: instrument description and initial measurement results," *Applied Optics*, **41**, 3725-3734.

Davis, A.B., R.F. Cahalan, J.D. Spinhirne, M.J. McGill and S.P. Love, 1999: "Off-beam lidar: An emerging technique in cloud remote sensing based on radiative Green-function theory in the diffusion domain," *Physics and Chemistry of the Earth - B*, **24**, 177-185.

McGill, M.J. and W.R. Skinner, 1997: "Use of multiple Fabry-Perot interferometers in an incoherent Doppler lidar," *Optical Engineering*, **36**, 139-145.

3 Tamás Várnai, CoI, UMBC/JCET, Voice: 301-614-6408. Fax: 301-614-6307

Education: Ph.D., Atmospheric & Oceanic Sciences, McGill University, 1996

Present position: 1999-present Research Assistant Professor, UMBC/JCET

Research: 3d radiative transfer, satellite data analysis

Cahalan, R. F., M. McGill, J. Kolasinski, T. Várnai, and K. Yetzer, 2004: THOR – Cloud Thickness from Offbeam Lidar Returns. *J. Atmos. Ocean. Tech.*. (In press)

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Várnai, T., and A. Marshak, 2002a: Observations of three-dimensional radiative effects that influence satellite retrievals of cloud properties. *Időjárás (Quart. J. Hungarian Met. Service)*, **106**, 265-278.

Várnai, T., and A. Marshak, 2002b: Observations of three-dimensional radiative effects that influence MODIS cloud optical thickness retrievals. *J. Atmos. Sci.*, **59**, 1607-1618.

Várnai, T., and A. Marshak, 2001: Statistical analysis of the uncertainties in cloud optical depth retrievals caused by three-dimensional radiative effects. *J. Atmos. Sci.*, **58**, 1540-1548.

Várnai, T., 2000: Influence of three-dimensional radiative effects on the spatial distribution of shortwave cloud reflection. *J. Atmos. Sci.* **57**, 216–229.

- 4 Jacobo Marcos Sirota, CoI**, Sigma Space Corp., Voice: 301-552-6300, Fax: 301-577-9466
 Education: Ph.D., Aeronautics and Astronautics, 1990
 Present position: 1997-present President and CEO, Sigma Space Corp.
 Research: lidar, laser ranging, molecular spectroscopy, optical instrumentation
 Awards & experience: System Engineer for the Stellar Reference System for ICESAT GLAS instrument
- Wang, W. F., and J. M. Sirota, 2002: Perturbative study of Spectral Line Shapes Involving Line-Mixing and Collision-Duration Asymmetry”, *Journal of Chemical Physics*, **116**, 532-537.
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- 5 Josefino C. Comiso, CoI**, NASA/GSFC/Code 971, Voice: 301-614-5708, Fax: 301-614-5644
 Education: Ph.D. in Physics, University of California at Los Angeles, 1972
 Present position: 1979-pres, Senior Res. Sci., Lab. For Hydrospheric Proc., NASA/GSFC
 Research: satellite analysis, air-sea ice interaction, radiative transfer in sea ice and snow
 Awards & experience:
 2003,1982 - NASA Group Achievement Award
 2004,2000,1996,1994,1991,1987 - Special Service, Performance Awards, NASA GSFC
 1988 - Peer Award for Best Paper, Laboratory for Oceans, NASA/GSFC
 Chief Scientist: NASA Aircraft Okhotsk Sea and Antarctic Campaigns, 2003 and 2004
 PI/Team member of the AMSR-E facility instrument for EOS-Aqua and ADEOS-2
- Comiso, J. C. and C. L. Parkinson, Satellite observed changes in the Arctic, *Phys. Today*, **57**(8), 38-44, 2004.
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- Yang, J., J.C. Comiso, D. Walsh, R. A. Krishfield, and S. Honjo, Storm-driven mixing in the upper Arctic Ocean and its relation to the Arctic Oscillation, *J. Geophys. Res.*, **109**, C04008, doi:10.1029/2001JC001248, 2004.

Current and Pending Research Support From All Other Sources

1. Principal Investigator

Current

NASA/RSP and NASA/EOS, 2004-2007, \$1023K.

Title: I3RC Workshops and 3D Community Tools Applied to Assessments and Improvements of Cloud Retrievals From Terra, Aqua, and THOR Offbeam Data

Co-PI: A. Marshak, Co-I's: K. F. Evans, L. Oreopoulos, T. Várnai, and G. Wen.

Current

US Dept. of Energy, ARM Program, 2003-2006, \$420 K.

Title: Advances in 3-Dimensional Atmospheric Radiation

Co-I's: L. Oreopoulos and G. Wen.

Note: Neither project above funds any instrument development, or have any overlap with THOR4Ice proposed funding.

Pending – None

2. Co-Investigators

Current/pending funding for Comiso:

NASA-EOS Facility AMSR-E Team Validation project

Title: "Antarctic AMSR-E Sea Ice" AASI Validation Program

Funding for 2005: TBD

NASA NRA-00-OES-05 (First of a three year proposal)

Title: "Response of Sea Ice and Marine Ecosystem to the Observed Warming"

Trends in the Arctic" Co-PI Glenn Cota/Old Dominion University

Funding extended to 2004: \$167,000

NASA-NRA-03-OES-02 (Earth System Science Research using Data and Products from Terra, Aqua, and ACRIM satellites), PI - J. C. Comiso,

Title: "Maintenance of the Bootstrap Algorithm and optimizing its performance" Funded for \$375K, first year.

Current/pending funding for Sirota:

NASA Upper Atmosphere Research Program, 2003-2004. \$130K.

Title: Laboratory Spectroscopy For Upper Atmosphere Research

Current/pending funding for McGill:

Current

NASA Code YS, Co-PIs: M. McGill & Y. Hu

\$400K/year, FY04-06

level of effort: McGill 50%.

Multi-Instrument Data Analysis and Synthesis (MIDAS), combining lidar and imager data in preparation for CALIPSO-MODIS data synergy.

Current

Goddard IR&D, PI: M. McGill

\$175K, FY05

level of effort: McGill 15%.

UAV lidar development for next-generation suborbital platforms.

Pending

NASA Code YS, PI: M. McGill

\$635K, FY05-07

level of effort: McGill 20%.

Cloud Physics Lidar measurements in support of Aura and A-Train validation.

Pending

NASA Code YS, PI: M. McGill

\$860K, FY05-07

level of effort: McGill 15%.

Lidar measurements from a UAV platform in support of Aura and A-Train validation.

Pending

NASA Code YS, PI: M. McGill

\$515K, FY05-07

level of effort: McGill 35%.

Cloud Physics Lidar measurements in support of Tropical Cloud Systems and Processes (TCSP).

Other Co-Is: none.